TECHNICAL MEMORANDUM (NASA) 26

SIMULATION ANALYSIS OF A MICROCOMPUTER-BASED, LOW-COST OMEGA NAVIGATION SYSTEM

Preprint of paper presented at the Bicentennial National Symposium of the Institute of Navigation, Warminster, Pennsylvania, April 28, 1976.

by

Robert W. Lilley
Richard J. Salter, Jr.
Avionics Engineering Center
Department of Electrical Engineering
Ohio University
Athens, Ohio 45701

May 1976

Supported by

National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia
Grant NGR36-009-017

TABLE OF CONTENTS

LIST OF FIGURES

SIMULATION ANALYSIS OF A MICROCOMPUTER-BASED, LOW-COST OMEGA NAVIGATION SYSTEM

Robert W. Lilley
Richard J. Salter, Jr.
Avionics Engineering Center
Department of Electrical Engineering
Ohio University
Athens, Ohio 45701

BIOGRAPHY

Dr. Robert W. Lilley is a Research Engineer with the Avionics Engineering Center at Ohio University, working in the areas of aircraft navigation and landing systems. Current activity emphasizes low-cost, low-complexity systems for Omega navigation.

Mr. Richard J. Salter, Jr., is a Graduate Research Associate with Avionics Engineering at Ohio University, specializing in digital circuitry applied to Omega navigation receivers.

Both authors work under sponsorship of NASA Langley Research Center in the Joint University Program for Air Transportation Systems. Both are private pilots and thus have a very personal interest in aircraft navigation systems.

ABSTRACT

The current status of research on a proposed microcomputer-based, low-cost Omega Navigation System (ONS) is described. The design approach emphasizes minimum hardware, maximum software, and the use of a low-cost, commercially-available microcomputer. Design objectives are to provide an accurate navigation aid for general aviation in the $1000 price range.

Previous reported research has resulted in the development of a very low-cost Omega sensor processor [1,2,3,4]. Currently under investigation is the implementation of a low-cost navigation processor and its interface with the sensor to complete the hardware-based Ohio University ONS. The fundamental concept under investigation in this study is: If navigation processor functions can be performed by an inexpensive microcomputer, how many of the sensor processor functions can also be handled by innovative software?

To explore this concept, computer simulation of sensor processor functions is underway. An input data base of live Omega ground and flight test data has been created. The Omega sensor and microcomputer interface modules used to collect the data are functionally described. Automatic synchronization to the Omega transmission pattern is described as an example of the algorithms developed using this data base.

INTRODUCTION

Ongoing work at the Avionics Engineering Center, Ohio University, is aimed at developing a simplified Omega Navigation System (ONS) in the $1000 price range for use in general aviation aircraft. A low-cost Omega sensor processor and unique hardware phase-processing techniques have been developed and reported. See Burhans [1], Chamberlin [2,3] and Lilley [4].

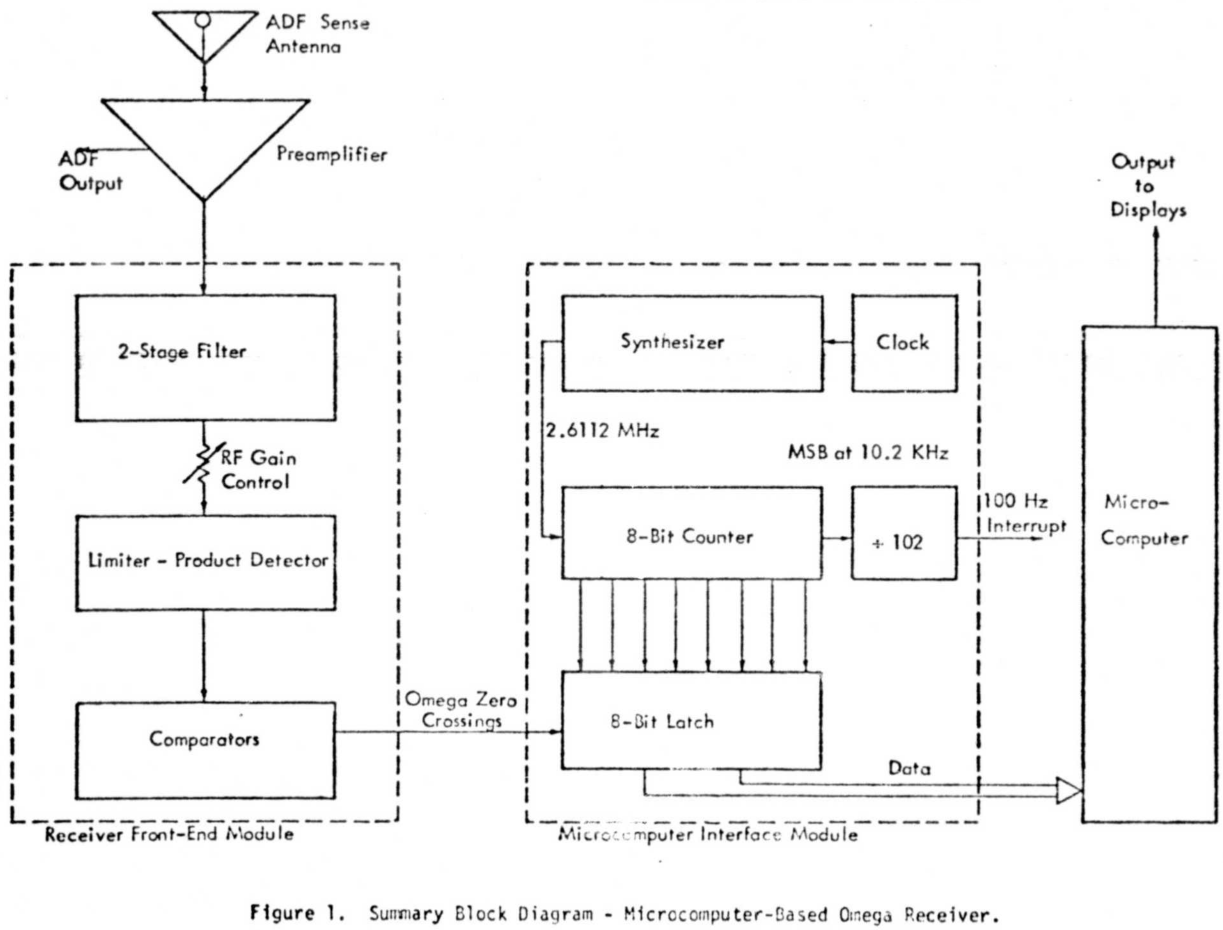

Figure 1. Summary Block Diagram - Microcomputer-Based Omega Receiver.

In a related effort, a software-based ONS using an inexpensive microcomputer and minimum receiver hardware is now being explored. Computer simulations of the proposed ONS are underway which use as a data base live Omega phase data collected with the Ohio University Omega sensor and microcomputer interface modules. Once the navigation algorithms have been fully developed in FORTRAN language, they will be translated into microprocessor code and loaded into the dedicated ONS microcomputer, first as volatile programming, subject to change, and later as read-only-memory programs.

This paper describes the Omega sensor module, microcomputer interface module, the establishment of the data base, and concludes with an example of the algorithms being developed. Operational results and low-cost considerations are emphasized throughout.

The authors acknowledge NASA/Langley Research Center which has supported this work under Grant NGR-36-009-017 for the application of VLF techniques to general aviation air transportation systems.

OMEGA RECEIVING SYSTEM

Figure 1 illustrates in general form the receiving system to be described in this paper. To minimize cost and complexity of installation, the system is designed to share the sense antenna of an aircraft automatic direction-finder (ADF) receiver.

The preamplifier module, located very near the antenna, provides Omega signal to coaxial cable at low impedance. Simultaneously, the preamplifier outputs a signal appropriate for the sense antenna input of the ADF receiver. Omega signals arrive at the receiver front-end module which (1) powers the preamplifier through the signal cable, (2) amplifies the Omega signal further and filters to provide approximately a 30 Hz bandwidth and (3) produces output pulses coincident with Omega signal zero-crossings. After processing in the microcomputer interface module, the resulting Omega phase data is passed to a digital tape recorder (in the simulation configuration) or to the microcomputer as input to the sensor and navigation algorithms.

PREAMPLIFIER MODULE

The preamplifier utilizes a field-effect transistor circuit providing a gain of 20 decibels at the 10.2 KHz frequency. The phase shift at this frequency is adjusted for zero degrees. At the ADF output, zero phase shift is seen across the ADF band, and the net gain is approximately -6 decibels. See Figure 2 for details of preamplifier circuitry and Figure 3 for performance curves [5].

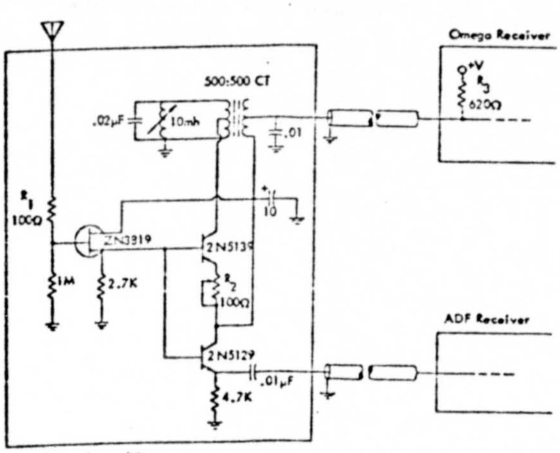

Figure 2. Omega/ADF Preamplifier Circuitry.

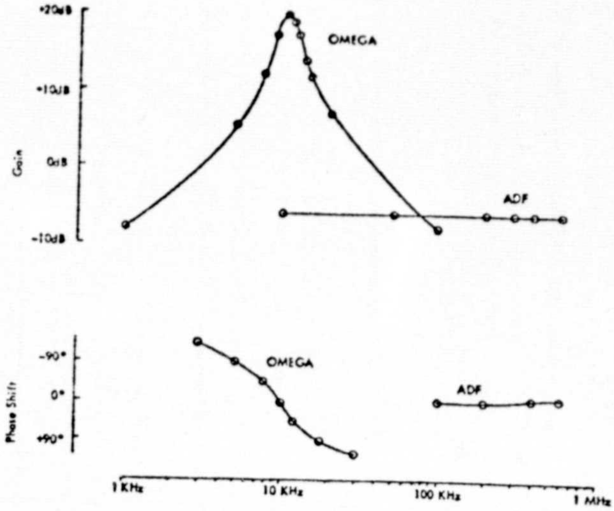

Figure 3. Omega/ADF Preamplifier Performance.

RECEIVER FRONT-END MODULE

The front-end module, described in detail by Burhans [1] provides additional gain, indication of signal strength, and digital pulse outputs at Omega signal zero-crossings. The unit consists of three integrated-circuit chips plus two ceramic filters providing a bandwidth of approximately 30 Hz at 10.2 KHz. See Figure 4 for the response curve and Figure 5 for a summary of front-end module specifications.

The preamplifier and front-end module have been bench- and flight-tested as reported by Wright [6]. Omega phase data taken from the 30 Hz bandwidth system has been analyzed and reported by Zervos [7].

MICROCOMPUTER INTERFACE MODULE

The microcomputer interface module performs the functions of phase detection and data sampling. It generates microcomputer interrupts for reading the phase data into the microcomputer.

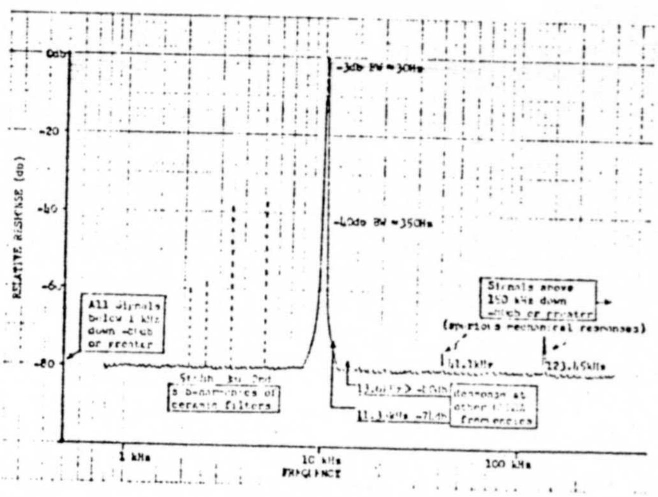

Figure 4. 10.2 KHz Filter-Amplifier Response.

FILTER-AMPLIFIER	Frequency Response	-3 dB, 30 Hz ±5Hz at 10.2 KHz -40 dB, < 400 Hz -70 to -80 dB at 11.33 and 13.6 KHz when tuned for Omega 10.2 KHz
	Gain	50 dB low, 70 dB high (adjustable range 40 dB)
	Phase	Tunable or adjustable
LIMITER-COMPARATOR	Limiter Gain	55 dB
	Comparator Gain	56 dB
	Comparator Phase Threshold	< 1 μv at antenna
	Analog Limiter Output	150 mv at 50 ohms
	Analog Envelope Output (operating range)	3 to 7 volts (±.5V) 80 dB (1 μv to 10,000 μv at antenna)
RECEIVER NOISE LEVEL		Less than 1 microvolt
RECOMMENDED INPUT RANGE		1 μv to 10,000 μv
RECOMMENDED ANTENNA SENSITIVITY		Effective Height of 1 Meter

Typical observed atmospheric noise level with 1 μv/meter E-field, antenna at 10.2 KHz ----- 10 μv to 100 μv in 30 Hz bandwidth

Figure 5. Receiver Front-End Specifications Summary.

As a special case of a multiple-frequency ONS, a functional description will be given for a 10.2 KHz single-frequency system. However, the described techniques are directly extendible to the multiple-channel case by simply deriving one additional clock frequency per channel from the existing common reference oscillator (TCXO). A further specialization employed here is the use of a $2^8 \times 10.2$ KHz = 2.6112 MHz reference clock to obtain 8-bit data word lengths. Longer or shorter word lengths can be obtained by using higher or lower reference clock frequencies.

For design generality, the clock frequency needed for the phase detector's reference counter is presently derived from a 5 MHz TCXO and a rate multiplier countdown chain. A multiple-frequency system could utilize a common TCXO and multiple synthesizer chains. To obtain 2.6112 MHz, the 5 MHz is multiplied by 0.52224 in five decades of binary-coded-decimal rate multipliers. The rate multiplier provides for any multiplication factor between 0.1 and 0.9 using BCD inputs to set the output rate. The output contains the required number of pulses in unit time, but due to the basic operation of the rate multiplier, the output pulses are not evenly spaced on the time axis. Phase jitter, therefore, is inherent. However, the amount of jitter introduced is thought to be insignificant at the 8-bit processing level. A single crystal oscillator circuit will be implemented in the final ONS design.

PHASE DETECTION

The phase measurement of each Omega zero-crossing with respect to a local reference clock is performed in an open loop fashion as shown in Figure 6a. The functional description of the phase detection process is as follows: A clock signal of frequency $2^8 \times 10.2$ KHz = 2.6112 MHz is applied to an eight-stage binary ripple counter. The output of the first stage (LSB) of this binary divider is, therefore, a square wave of frequency $2^7 \times 10.2$ KHz. Similarly, the last stage output (MSB) is changing at a $2^0 \times 10.2$ KHz rate. The eight counter outputs are used as data inputs to an 8-bit latch.

The latch is composed of eight edge-clocked D flip-flops which are simultaneously clocked by the incoming Omega zero-crossings supplied from the receiver front-end. Since data is transferred from the D inputs to the Q outputs of the latch only when it is clocked by an Omega zero-crossing, an 8-bit word representing the phase of the incoming Omega edge with respect to the local clock appears at the latch output approximately 10,200 times per second.

Note that no attempt is made to make absolute phase measurements; only a measurement-to-measurement relative phase is obtained at this point. For example, if the Omega signal was noise-free (a stable 10.2 KHz signal), the latch would be clocked at regular intervals of $T = 1/10.2 \text{ KHz} = 9.8 \times 10^{-5}$ seconds. This would result in the output remaining constant for each measurement (see Figure 7a). This constant number would represent the initial phase offset between the incoming 10.2 KHz signal and the $2^8 \times 10.2$ KHz reference clock. Realistically, however, since Omega signals off-the-air are contaminated by noise (phase jitter), the Omega zero-crossings used to clock the data latch will be irregularly spaced in time. This results in nonconstant phase measurement numbers at the latch output, the short term variations in this phase measurement being caused by the noisy Omega signal (Figure 7b).

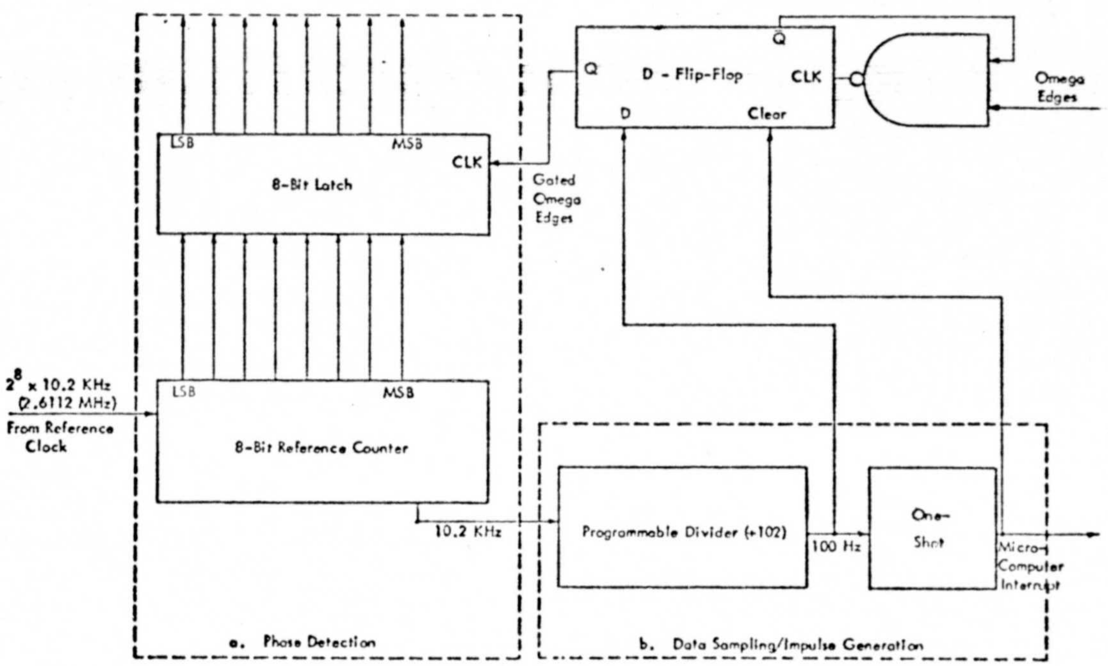

Figure 6. Microcomputer Interface Module.

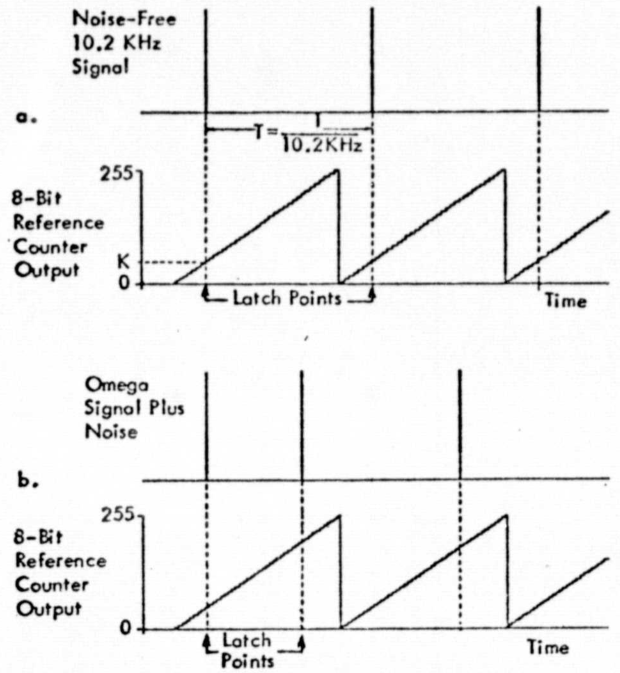

Figure 7. Phase Detection Waveforms.

DATA SAMPLING AND INTERRUPT GENERATION

There are several considerations which suggest sampling the phase measurements at a rate slower than the 10.2 KHz carrier rate.

(1) The high degree of correlation of the Omega signal makes it unnecessary to use the phase measurement from every cycle of the carrier.

(2) Sampling of the data provides, in effect, an amount of needed integration if the sampling rate is slow enough to undersample short-term phase variations due to noise.

(3) Using the data at the maximum available raw-data rate implies a prohibitively high interrupt rate for most microcomputers.

The choice of a particular sampling rate is based on these considerations.

In this particular hardware implementation, a sampling frequency of 100 Hz has been chosen for the following reasons:

(1) A front-end receiver bandwidth of 30 Hz implies that samples must be taken at greater than a 60 Hz rate for the sampled signal to contain all the information of the raw input signal (Nyquist Rate).

(2) Previous experience with hardware processing schemes indicates that about 10 bits (1024 samples) of integration is optimum for this receiver configuration [3]. A 100 Hz sampling rate accepts every 102nd phase measurement, in effect, resulting in nearly 7 bits of integration.

(3) 100 Hz is an acceptable microcomputer interrupt rate, and it is easily generated from the existing receiver timing circuitry.

Figure 6b shows the derivation of the 100 Hz sampling frequency from existing timing signals. The ripple counter's MSB which is toggling at a 10.2 KHz rate is further divided by 102 in a programmable divider chain. Similarly, for a multiple-frequency system, this same 100 Hz could be used to sample simultaneously the other data channels as well. The resulting 100 Hz square wave is then fed to a positive-edge trigger to generate a microcomputer interrupt every 10 msec.

To insure that the data at the output of the latch is stable when the microcomputer interrupt occurs (i.e., to insure that the pseudo-random Omega zero-crossings do not clock new phase measurements through the latch while the data is being read), the Omega zero-crossings are gated with the interrupt pulse as shown in the microcomputer interface module block diagram in Figure 6.

In keeping with the design objectives of low-cost, simplicity and small size, this single-frequency version of the microcomputer interface module has been brassboarded using ten TTL integrated circuit chips. Further plans call for a CMOS version of this module to be implemented using just four chips.

DATA BASE

Before attempting to use a commercially available microcomputer dedicated to the ONS, it is desirable to simulate the navigation system functions and develop efficient (and simplified) algorithms using a high level programming language and a multipurpose computer. The classical approach to system simulations is to use computer number generators to approximate the signal and noise inputs from the known statistics of both. This approach would involve passing an Nth order Markov signal (highly correlated Omega) and White Gaussian noise plus impulse noise (VLF atmospheric noise) through an Mth order bandpass filter (narrowband receiver front-end).

However, a much more powerful approach has been taken to insure that the data for the navigation processor simulations is exactly the same data that will ultimately be seen by the dedicated microcomputer. Since the Omega sensor and microcomputer interface modules of the proposed ONS have been fully developed in hardware and flight tested, it has been possible to use these same modules that will supply the navigation processor with Omega data to collect actual off-air data for use in the navigation processor simulations. For the collection of ground and flight data the Omega sensor and microcomputer interface modules have been used to supply Omega phase data to an incremental magnetic tape recorder. The microcomputer interrupt pulse is used as the tape recorder "write" pulse.

Twenty-four continuous hours of ground data and five hours of flight data have been collected as a data base for simulations. The Omega sensor and microcomputer interface modules and Kennedy tape unit were installed in an Ohio University DC-3 flight test aircraft and used for airborne data collection.

NAVIGATION PROCESSOR SIMULATION

One goal of this project is to investigate the concept of a microcomputer-based ONS; that is, to develop a completely software-based system requiring as little hardware as possible. Previously reported research [4] has resulted in a hardware sensor processor including a hardware Omega synchronization scheme and correlation detector. The proposed software-based system would perform these functions as well as Skywave Correction, Position Location, Coordinate Conversion, and Cockpit Display Generation via software routines. Following the completion of this study, a direct comparison of hardware versus software performance will be possible. A quantitative evaluation of the hardware/software engineering tradeoffs in terms of performance, cost, and physical size can be performed.

An example of the ONS algorithms being developed is the automatic synchronization to the Omega transmission pattern which is described below.

AUTOMATIC SYNCHRONIZATION

The Omega system consists of eight stations transmitting on three frequencies in a fixed, time-multiplexed format. A unique pattern is formed by the scheduled length of each station's transmission which repeats every ten seconds (see Figure 8). Thus, to use the phase measurements supplied by the microcomputer interface module, some means must be provided for synchronizing the ONS timing with the Omega transmission pattern. Only after the ONS is "in sync" can the phase of each station's signal be followed by tracking loops to give position-fixing information.

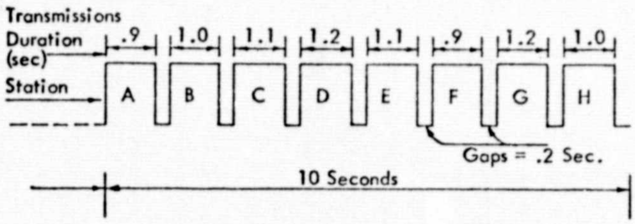

Figure 8. Omega Transmission Pattern.

It should be pointed out that precision sync (within ± 100 msec) is unnecessary. A .2 second gap between each transmission burst allows for propagation delays from transmitter to receiver without signal overlap into another station's time slot. Therefore, sync within ± 100 msec insures that only one station will be received during each of the eight time slots.

A description of the automatic synchronization procedure developed and simulated at Ohio University follows, and a logic flow diagram is given in Figure 9. Although the routine is described here in terms of a single-frequency system, the technique is applicable to a multiple frequency system as well. Performing the routine on multiple channels simultaneously would give the navigation processor a redundancy check. By averaging the results obtained for all channels, a best estimate of the sync point could be obtained.

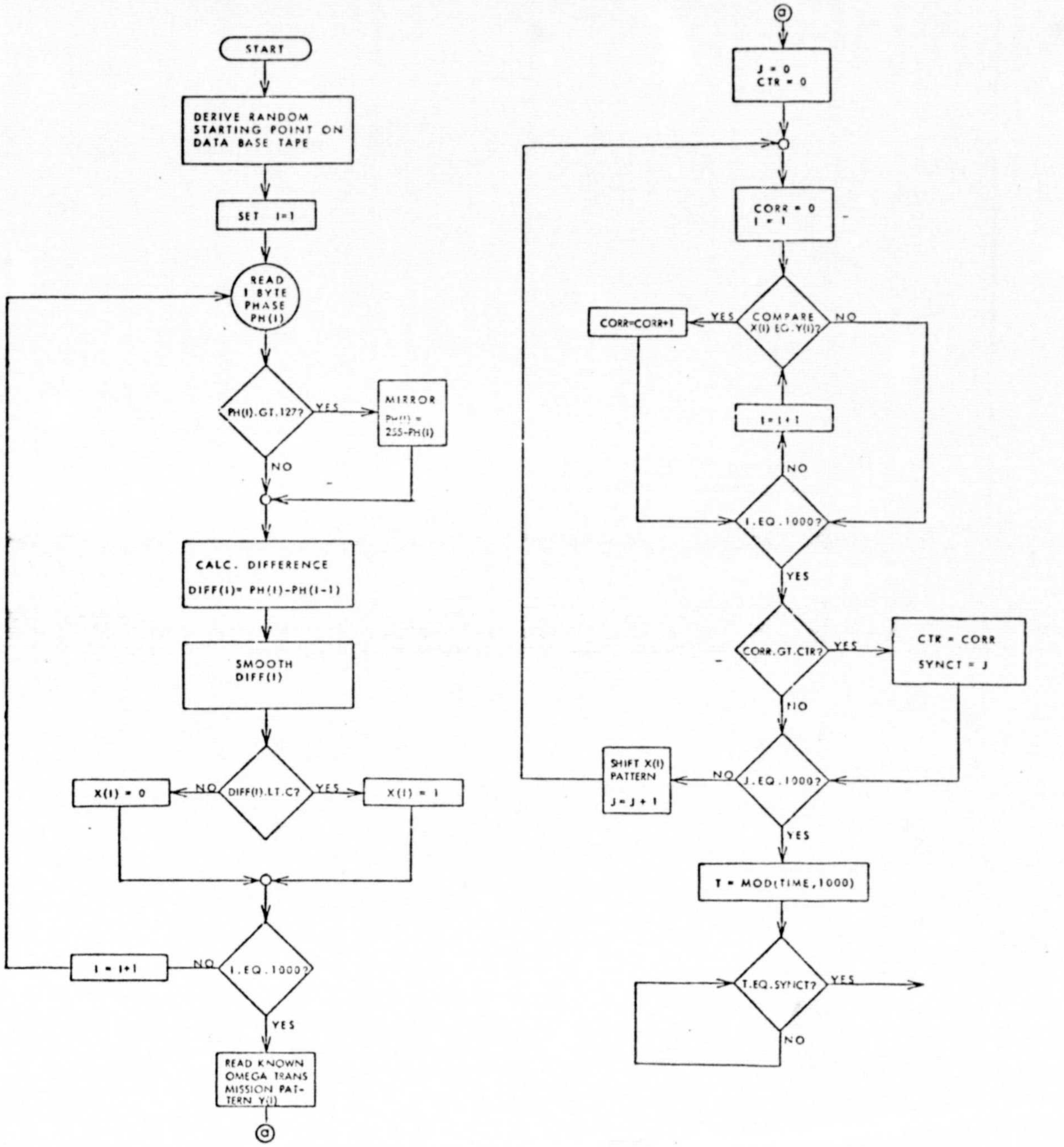

Figure 9. Automatic Synchronization Flow Chart.

To establish sync we must obtain a transmission pattern from the live data and shift the entire ten second frame until the live pattern coincides with the unique Omega transmission pattern stored in the computer. The live transmission pattern can be established by determining the amount of correlation between consecutive 10-msec phase samples. High correlation indicates the presence of a strong signal, while the lack of phase coherence is indicative of a weak signal or noise. The absolute value of phase measurements is meaningless during the sync process; only the phase correlation from sample to sample is useful in determining the live transmission pattern (i.e. in determining whether the sample point is signal or noise).

An Omega phase measurement is supplied by the microcomputer interface module every 10 msec (100 Hz sampling rate). Starting at a random point in time and taking data for ten seconds (one complete Omega frame) yields 1000 phase samples. This is all the information needed to accomplish sync: One ten second record containing 1000 bytes of phase data, each byte being 8-bits long. To simulate a random ONS start time, a call to a subroutine returns two random numbers. These represent the number of records and bytes in the data base tape to be skipped to get to the random starting point. Beginning at this point on the data base tape, 1000 phase bytes are read.

The Omega signal is contaminated with noise, causing a series of measurements to result in a dispersion of phase points rather than a constant value. If the phase of a signal with respect to the receiver clock is near the 0 to 255 measurement extremes (near the "edge" of a cycle), the measured value may "bobble" between the 0-255 extremes. To remove this bobble each data point is "mirrored" about the 50% full scale value (mirrored about 127). Points at $x = 255$ are thus reflected to $255 - x = 0$. Since we are interested only in the phase correlation and not the absolute value of phase, the mirroring process merely puts the data into a better form from which the correlation can be determined.

A simple routine yielding a measure of the point-to-point correlation is to take the difference of each two successive phase points. That is, subtracting each measurement from the previous yields 1000 difference values: each difference is inversely proportional to the correlation between two sample slots.

By comparing each difference value to a predetermined "threshold constant", a decision can be made as to whether signal or noise exists in each 10-msec sample slot. However, it may be desirable to smooth or average the difference values over several sample slots before comparison to the threshold constant is made. If the difference is less than the threshold, a "1" is stored in the sample slot (low difference ⟶ high correlation ⟶ signal present). If the difference is greater than the threshold, a "0" is stored in the slot. After all 1000 comparisons have been performed, a pattern of 1000 1's and 0's represents the signal and noise sample slots, respectively.

Note that the 1000 bits can be stored in 125 8-bit bytes of memory (an amount of storage not prohibitive for simple microcomputer systems). Also bear in mind that virtually the entire microcomputer will be dedicated to the autosync routine during the sync process, since no Omega navigation information is available until after sync is complete.

The 1000 sample bits are next compared to the stored Omega pattern in a bilevel correlation process. Use is made of both time slot and transmission gap information; whenever the sample slot binit is equal to the stored slot binit, the correlation counter is incremented by one. After all 1000 slots have been compared, the stored pattern is shifted by one slot and the comparison process is repeated. This shift and compare iteration is continued until all 1000 possible shifted patterns have been tested. The number of shifts necessary to obtain the highest bilevel correlation value represents the starting point for the "A" time slot.

Having gone to the sync point in the data, Figure 10 shows the resultant 1000 byte record plotted 10 points per line. The higher the signal-to-noise ratio of the station being received in each time slot, the less dispersion there is in the phase points plotted.

For a confidence measure, the entire sync process can be performed several times and a best estimate of the sync point computed. If multiple frequencies are available, the process can be performed on each channel and the sync points averaged (or a sync point can be considered acceptable only if it results on 2 out of 3 channels, etc.). Another possibility is to save the second highest correlation value as well as the highest, and consider the sync point acceptable only if the highest value is better than the second highest by a predetermined amount.

Nothing has yet been said about operator assistance during the sync process. However, the operator's a priori knowledge of which stations are on the air and which ones will be well-received in his particular geographic area can be incorporated into the creation of the unique transmission pattern stored in the computer. This facilitates the bilevel correlation process, resulting in a more accurate sync point.

Besides the sync point information made available by the auto-sync routine, a signal-to-noise ratio measurement can be derived very simply from the bilevel sample slot pattern. After the sync point has been determined, the first 90 binits in each time slot can be summed; the sum obtained for each time slot is proportional to the SNR in each time slot. This information can be used by the navigation processor to automatically determine which stations are best for navigation (in the SNR sense).

After the sync point has been determined and the ONS timing synchronized with the transmission pattern, the 125 bytes of sample slot binits need not be saved unless it is desired to check the sync point at later times to insure that sync is maintained. Several methods for periodically checking the sync point are now being investigated.

In summary, the technique presented requires very simple microcomputer instructions (compare, subtract, and shift); uses very little storage (125 bytes maximum); usually accomplishes sync in less than 20 seconds (depending on the number of redundancy checks desired). The routine has demonstrated acceptable accuracy (within ± 100 msec) using the Omega data base described earlier. Continued research utilizing decision theory techniques is ongoing to determine the threshold constant in an optimal fashion. Several types of data smoothing routines have been used to obtain the smoothed difference values; a 9-point straight averaging filter seems to give best results.

FUTURE ACTIVITY

The automatic synchronization algorithm is only the beginning. Immediately following acceptance of the preliminary sync algorithm, work will begin on the Omega tracking loop software, to be followed by navigation algorithms and display drivers. Current plans call for physical implementation of the microcomputer after simulations of the sensor processor functions are complete. Flight tests of the software sensor processor are planned for summer 1976.

ACKNOWLEDGEMENTS

The work reported here was performed under NASA Contract NGR 36-009-017, the Joint University Program in Air Transportation Systems sponsored by Langley Research Center. The Avionics Engineering Center, directed by Dr. Richard H. McFarland for Ohio University, maintains an Omega Project Team headed by Ralph W. Burhans, Project Engineer. Various members of the team provided input and suggestions during preparation of this paper.

REFERENCES

[1] Burhans, R. W., "Low-Cost, High-Performance VLF Receiver Front-End", Technical Memorandum (NASA) 18, Avionics Engineering Center, Department of Electrical Engineering, Ohio University, Athens, Ohio, September, 1975.

[2] Chamberlin, K., "Binary Phase Locked Loops for Omega Receivers", Proceedings of the Second Omega Symposium, Washington, D. C., November, 1974.

[3] Chamberlin, Kent A., "Digital Correlation Detector for Low-Cost Omega Navigation", Technical Memorandum (NASA) 19, CR144956, Avionics Engineering Center, Department of Electrical Engineering, Ohio University, Athens, Ohio, February, 1976.

[4] Lilley, R. W., "Binary Processing and Display Concepts for Low-Cost Omega Receivers, Journal ION, Vol. 22, No. 3, Fall, 1975.

[5] Wright, L., "Improvements for Omega RF Preamplifiers", Technical Memorandum (NASA) 24, Avionics Engineering Center, Department of Electrical Engineering, Ohio University, Athens, Ohio, in progress.

[6] Wright, L., "Flight Test of 4 Hz and 30 Hz Omega Receiver Front-End", Technical Memorandum (NASA) 21, Avionics Engineering Center, Department of Electrical Engineering, Ohio University, Athens, Ohio, February, 1976.

[7] Zervos, A. K., "A Performance Simulation of a Potential Class of Low-Cost Omega/Air Data Navigation Systems", M.S. Thesis, Princeton University, September, 1975.

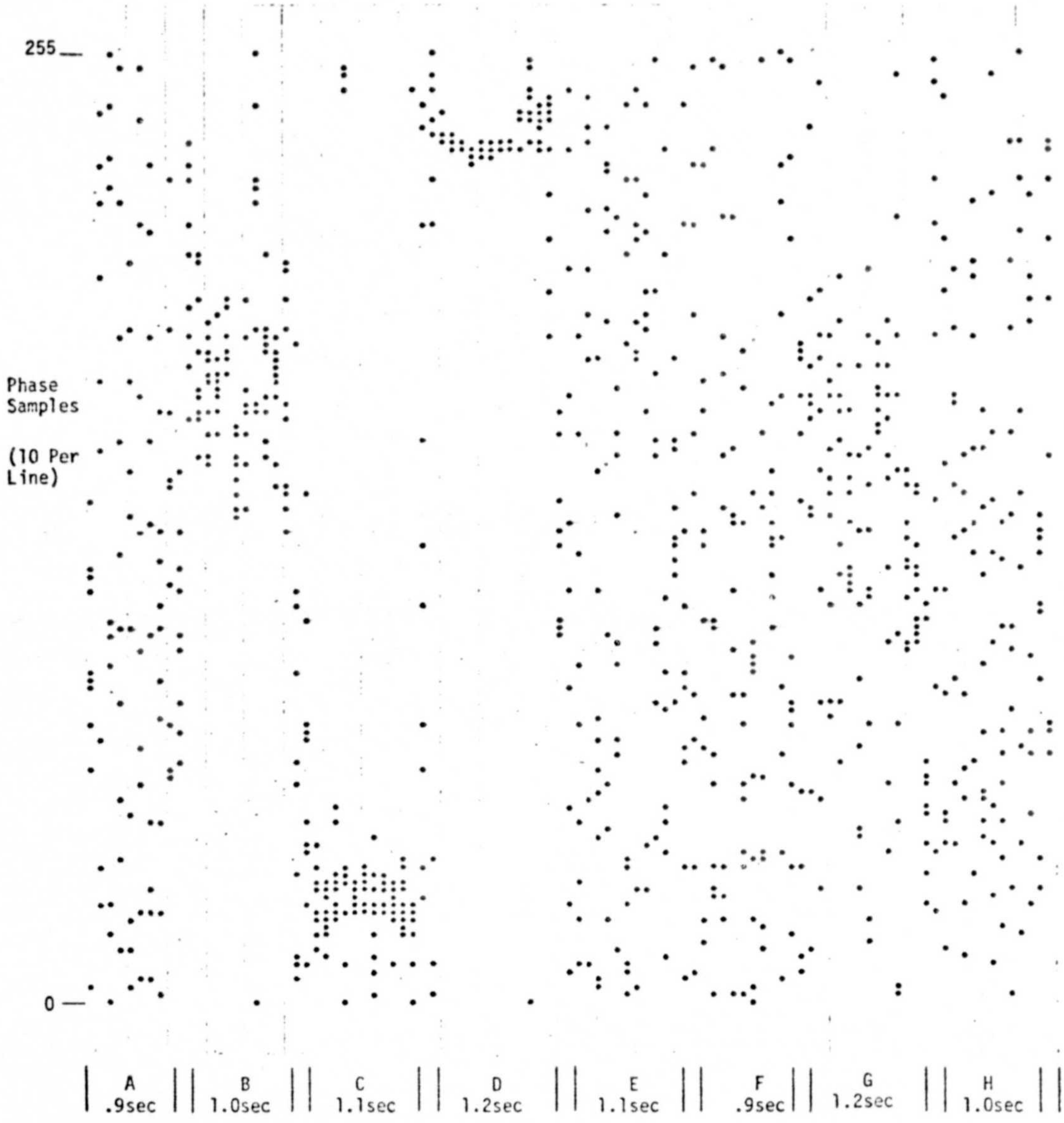

Figure 10. One Record of Omega Phase Data (1000 Bytes).